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Abstract

We developed a unified statistical framework for deriving signal processing methods. In electromagentics we developed methods for source tracking using an EM vector-sensor antenna; we designed such an antenna of compact shape. In radar we derived Cram/'er-Rao bounds for estimating a target range, velocity, and direction; developed a novel parametric approach for estimating and mitigating interferences in STAP. In communications we considered space-time fading channel estimation and symbol detection in spatially correlated noise; finite-length MIMO adaptive equalization; and channel estimation for OFDM wireless systems. In acoustics we considered wideband source localization using a distributed acoustic vector-sensor array; source direction with an array near a boundary; and noise-reduction algorithm for dual-microphone systems. We analyzed the cross-correlations between wide-band noise components of a vector sensor. We applied our results to various biomedical problems. Several successful transitions resulted from this project.

General Signal Processing:

The performance breakdown of subspace-based parameter estimation methods can be naturally related to a switch of vectors between the estimated signal and noise subspaces (a "subspace swap"). In [1] we derive a lower bound for the probability of such an occurrence and use it to obtain a simple data-based indicator of whether or not the probability of a performance breakdown is significant. We also present a conceptually simple technique to determine from the data whether or not a subspace swap has actually occurred, and to extend the range of SNR values or data samples in which a given subspace method produces accurate estimates.

Generalized multivariate analysis of variance (GMANOVA) and related reduced-rank regression are general statistical models that comprise versions of regression, canonical correlation, and profile analyses, as well as analysis of variance (ANOVA) and covariance in univariate and multivariate settings. It is a powerful and yet not very well known tool. In [2], we develop a unified framework for *explaining, analyzing,* and *extending* signal processing methods based on GMANOVA. We show the applicability of this framework to a number of detection and estimation problems in signal processing and communications, and provide new and simple ways to derive numerous existing algorithms for various applications. problems in signal processing. We also present a new application to flaw detection in nondestructive evaluation (NDE) of materials.

Electromagnetic Vector-Sensor Antenna Design:

In [3] we design a compact vector-sensing antenna that consists of 3 co-located orthogonal doubly loaded thin wire loops. We analyze power as well as balance between the magnetic and electric responses as functions of the antenna load and size. The loads that maximize the received power are shown to be, in general, different from those that are needed to equalize electric and magnetic responses. The consequences of this for the estimation of the direction of arrival are briefly discussed.

Coupling between two collocated orthogonal circular thin-wire loops is analyzed in [4], [5].

Classical theory of thin wire loops is used to obtain a general solution in matrix form for the Fourier coefficients of the loop currents. Analytical expression for currents induced through the mutual coupling is obtained for the case when all loop current harmonics higher than first can be ignored. It is found that strong coupling can exist for all loop current harmonics, except for the fundamental. It is also found that coupling for orthogonal collocated loop antennas depends on the relative locations of the loop terminals.

Electromagnetic Vector-Sensor Processing for Direction Finding:

We developed in [6] a beamformer employing a single electromagnetic vector sensor. This beamformer is of minimum-noise-variance type, and is used for interference rejection. It creates a beam focused in both direction and polarization that minimizes interference from undesired sources (e.g. jammers). In this way it can do the work of multiple scalar polarization-selective sensors. The key advantages of our beamformer over current systems are summarized in the paper.

In [7], [8] we presented a structure for adaptively separating, enhancing and tracking uncorrelated sources with an electromagnetic vector sensor. The structure consists of a set of parallel spatial processors, one for each individual source. Two stages of processing are involved in each spatial processor. The first preprocessing stage rejects all other sources except the one of interest, while the second stage is an adaptive one for maximizing the SNR and tracking the desired source. The preprocessors are designed using the latest source parameter estimates obtained from the source trackers, and a re-design is activated periodically or whenever any source has been detected by the source trackers to have made significant movement. Compared with conventional adaptive beamforming, the algorithm has the advantage that it is a "blind" scheme where no a priori information on any desired signal location is needed, the sources are separated at maximum SNR, and their locations are available. The structure is also well suited for parallel implementation. Numerical examples are included to illustrate the capability and performance of the algorithm.

Radar:

In [9], [10], we derived Cramér-Rao bound (CRB) expressions for the range (time delay), velocity (Doppler shift), and direction of a point target using an active radar or sonar array. First, general CRB expressions were derived for an arbitrary signal waveform and a noise model that allows both spatial and temporal correlation. We discussed the relationship between the CRB and ambiguity function for this model. Then we specialized our CRB results to temporally uncorrelated noise and the practically important signal shape of a linear frequency modulated (chirp) pulse sequence. We computed the CRB for a 3-dimensional array with isotropic sensors in spatially uncorrelated noise and showed that it is a function of the array geometry only through the "moments of inertia" of the array. The volume of the confidence region for the target's location was proposed as a measure of accuracy. For this measure, we showed that the highest (and lowest) target location accuracy is achieved if the target lies along one of the principal axes of inertia of the array. Finally, we compared the location accuracies of several array geometries.

In [11] we propose a novel parametric approach for modeling, estimation, and detection in space-time adaptive processing (STAP) systems. The proposed model is based on the Wold-like decomposition of 2-D random fields. It is first shown that the same parametric model that results from the 2-D Wold-like orthogonal decomposition naturally arises as the physical model in the problem of space-time processing of airborne radar data. We exploit this correspondence to derive computationally efficient fully adaptive and partially adaptive detection algorithm. Having estimated the models of the noises and interference components of the field, the estimated parameters are substituted into the parametric expression of the interference-plus-noise covariance matrix. Hence, an estimate of the fully-adaptive weight vector is obtained, and a corresponding test is derived. Moreover, we prove that it is sufficient to estimate only the spectral support parameters of each interference component in order to obtain a projection matrix onto the subspace orthogonal to the interference subspace. The resulting partially adaptive detector is simple to implement, as only a very small number of unknown parameters need to be estimated. The parametric interference mitigation procedure can be applied even when information in a single range gate is available, thus achieving high performance gain when the data in the different range gates cannot be assumed stationary.

The performance of the proposed methods is illustrated using numerical examples.

We present a new method of beamforming using the fractional Fourier transform in [12]. This method encompasses the minimum mean-squared error beamforming in the frequency domain or spatial domain as special cases. It is especially useful for applications involving chirp signals such as signal enhancement problems with accelerating sinusoidal sources where the Doppler effect generates chirp signals and a frequency shift, and active radar problems where chirp signals are used as the transmitted signal. Numerical examples demonstrate the potential advantage of this method over the ordinary frequency or spatial domain beamforming for a moving source scenario.

Due to the high-dimensionality of hyper-spectral data, feature extraction is an important issue in hyper-spectral data classification. In [13], we evaluate and compare the performance of the well-known principle component analysis (PCA) and Fisher's linear discriminant analysis (FLD) for hyper-spectral data feature extraction. Based on this, we propose a new feature extraction method utilizing the overall geometric shape of a reflectance curve. The new feature extraction method has three advantages. Firstly, it is physically meaningful. Secondly, since the new feature is extracted by exploiting the similarity inherited in the overall geometric shape of hyper-spectral data, samples of the same class form compact clusters in the new feature space, and hence accurate classification can be achieved. Thirdly, label information of training samples is not required in our feature extraction procedure. As a direct result, the new feature is unlikely to over-fit training samples.

Communications:

We present in [14] maximum likelihood (ML) methods for space-time fading channel estimation with an antenna array in spatially correlated noise having unknown covariance; the results are applied to symbol detection. The received signal is modeled as a linear combination of multipath-delayed and Doppler-shifted copies of the transmitted waveform. We consider structured and unstructured array response models, and derive the Cramér-Rao bound for the unknown directions of arrival, time delays, and Doppler shifts. We also develop methods for spatial and temporal interference suppression. Finally, we propose coherent matched-

filter and concentrated-likelihood receivers which account for the spatial noise covariance, and analyze their performance.

We propose in [15], [16] finite-length multi-input multi-output adaptive equalization methods for "smart" antenna arrays using the statistical theory of canonical correlations. We show that the proposed methods are related to maximum likelihood reduced-rank channel and noise estimation algorithms in unknown spatially correlated noise, and to several recently proposed adaptive equalization schemes.

Space-time channel estimation is essential for communication systems which separate sources in the space domain in addition to time/frequency/code domains. In [17], we first develop a Maximum Likelihood (ML) estimator for the spatial channel transfer function in the presence of strong interference sources, for 3 different channel scenarios: no multipath, locally scattered multipath, and general multipath case. As expected, the ML estimator, which assumes planar wave-field for the signal, provides superior performance over the ML solution for the general multipath case. In order to maintain the robustness to the scenario, an algorithm for scenario/model determination is developed, and its performance is evaluated via simulations.

We develop in [18] a frequency-domain channel estimation algorithm for single-user OFDM wireless systems in the presence of interference. In this case, the received measurement is correlated in space with covariance matrix dependent on frequency. Hence, the commonly used least-squares algorithm is suboptimal. On the other hand, accurate estimation of the spatial covariance matrix in such a model using the multivariate analysis of variance (MANOVA) method would impose significant computational overhead, since it would require large number of pilot symbols. To overcome these problems, we propose to model the covariance matrix using a-priori known set of frequency-dependent functions of joint (global) parameters, resulting in a structured covariance matrix. We find the unknown parameters using the estimated generalized least-squares (EGLS) which estimates the interference covariance parameters using a residual method of moments (RMM) estimator and the mean (user channel) parameters by maximum likelihood (ML) estimation. Since our RMM estimates

are invariant to the mean, this approach yields simple non-iterative estimates of the covariance parameters while keeping the optimal statistical efficiency. Therefore, our algorithm outperforms the least-squares method in accuracy, and at the same time requires smaller number of pilots than the MANOVA method and thus has smaller overhead. Numerical results illustrate the applicability of the proposed algorithm. More recently we considered OFDM channel estimation in the presence of asynchronous interference case in [19].

In Discrete Multi-Tone (DMT) systems a cyclic prefix is added to the front of each modulated symbol-frame in order to partition the whole channel into many narrow independent subchannels. When the length of the cyclic prefix is shorter than the channel length, Inter-Carrier Interference (ICI) and Inter-Symbol Interference (ISI) will occur in the output signal. In [20] we present a Decision Feedback Equalizer (DFE) on a symbol level to deal with this problem. The DFE first removes the ISI. It then recovers the distortion caused by ICI. The advantage of this equalizer is that the cyclic prefix for the equalizer can be discarded thus leads to no bandwidth loss. Several simulation examples are presented to show the significant improvement of the equalized signal over the unequalized.

Acoustic Array Processing:

In [21] we considered the passive direction-of-arrival (DOA) estimation problem using arrays of acoustic vector sensors located in a fluid, at or near a reflecting boundary. We formulated a general measurement model applicable to any planar surface, derived an expression for the Cramér-Rao bound (CRB) on the azimuth and elevation of a single source, and obtained a bound on the mean-square angular error (MSAE). We then examined two applications of great practical interest: hull-mounted and seabed arrays. For the former, we used three models for the hull: an ideal rigid surface for high frequency, an ideal pressure-release surface for low frequency, and a more complex, realistic layered model. For the seabed scenario we modeled the ocean floor as an absorptive liquid layer. For each application we used the CRB, MSAE bound, and beampatterns to quantify the advantages of using velocity and/or vector sensors instead of pressure sensors. For the hull-mounted application, we showed that normal component velocity sensors overcome the well-known, low-frequency problem

of small pressure signals without the need for an undesirable "stand-off" distance. For the seabed scenario, we also derived a fast wideband estimator of the source location using a single vector sensor.

Most array processing methods require knowledge of the correlation structure of the noise. While such information may sometimes be obtained from measurements made when no sources are present, this may not always be possible. Furthermore, measurements made *in-situ* can hardly be used to analyze system performance before deployment. The development of models of the correlation structure under various environmental assumptions is therefore very important. In [22] we obtained integral and closed form expressions for the auto- and cross-correlations between the components of an acoustic vector sensor (AVS) for a wideband noise field, under the following assumptions concerning its spatial distribution: (i) azimuthal independence; (ii) azimuthal independence and elevational symmetry, and (iii) spherical isotropy. We also derived expressions for the cross-covariances between all components of two spatially displaced AVS's in a narrowband noise field under the same assumptions. These results can be used to determine the noise covariance matrix of an array of acoustic vector sensors in ambient noise. We applied them to a uniform linear AVS array to asses its beamforming capabilities and localization accuracy, via the Cramér-Rao bound, in isotropic and anisotropic noise.

We derived in [23], [24] fast wideband algorithms for determining the bearing and 3-D position of a target using a distributed array of acoustic vector sensors (AVS's) situated in free space or on a reflecting boundary. Each AVS locally estimates the bearing from its location to the target using a rapid wideband estimator we develop based on the acoustic intensity vector; adaptations of beamforming-based bearing estimators for use with an AVS are also discussed. The local bearing estimates are then transmitted to a central processor where they are combined to determine the 3-D position. Closed-form weighted least-squares (WLS) and re-weighted least-squares algorithms are proposed to achieve this. A bound on the mean-square angular error of the local bearing estimates is obtained, and used along with the data to adaptively determine the weights for the WLS routine. In addition, a measure of potential 3-D location performance for the distributed system is developed based on a

two stage application of the Cramér-Rao bound. The results are relevant to the localization of underwater and airborne sources using freely-drifting, seabed, and ground sensors. Numerical simulations illustrate the effectiveness of our estimators and the new potential performance measure. This work has led to a new transition with successful results, see below.

In [25], [26] we proposed an effective adaptive null-forming scheme for two nearby microphones in endfire orientation which are used in many kinds of hearing devices such as hearing aids and noise cancellation in cockpit. This adaptive null-forming scheme is mainly based on an adaptive combination of two fixed polar patterns that act to make the null of the combined polar pattern of the system output always be toward the direction of the noise. The adaptive combination of these two fixed polar patterns is accomplished by simply updating an adaptive gain following the output of the first polar pattern unit. The value of this gain is updated by minimizing the power of the system output and related adaptive algorithms to update this gain are also given in this paper. We have implemented this proposed system on the basis of a programmable DSP chip and performed various tests. Theoretical analyses and testing results demonstrated the effectiveness of the proposed system and the accuracy of its implementation.

In [27] we investigate spectral contrast enhancement techniques and their implementation complexity. Three algorithms are dealt with in this paper. The first is the method described by Baer, Moore and Gatehouse. Two alternative methods are also proposed and investigated in this paper from a practical application and implementation point of view. Theoretical analysis and results from laboratory, simulation, and subject listening show that spectral contrast enhancement and performance improvement can be achieved by use of these three methods with the appropriate selection of their relevant p

Biomedical Applications:

In [28], [29] we derived Cramér-Rao bounds on the errors of estimating a single dipole's location and moment using EEG, MEG and combined EEG/MEG modality. We used realistic head models based on knowledge of surfaces separating tissues of different conductivities,

obtained from magnetic resonance (MR) or computer tomography (CT) imaging systems. The electric potentials and magnetic field components at the respective sensors were obtained as functions of the source parameters through integral equations. These equations were formulated for solution by the boundary or the finite element method (BEM or FEM), with a weighted residuals technique. We presented a unified framework for the measurements computed by these methods that enables the derivation of the bounds. The resulting bounds may be used, for instance, to construct the confidence regions in dipole localization, and to choose the best configuration of sensors for a given patient and region of expected source location. Numerical results demonstrated an application for showing regions of good and poor expected accuracy in estimating the source parameters, based on a real EEG/MEG system.

Techniques based on electroencephalography (EEG) measure the electric potentials on the scalp and process them to infer the location and signal of the underlying neural activity. The accuracy of estimating these parameters is highly sensitive to the uncertainty in the conductivities of most of head tissues. In [31] we present methods based on statistical processing that allow simultaneous estimation of the ratios of the layer conductivities and source signal using EEG array data. We assume the classical concentric 4-sphere model to approximate the head geometry, and consider that the position of the source is known. Under these conditions, we apply the maximum likelihood (ML) technique and the Bayesian approach to obtain, respectively, the ML and maximum a posteriori (MAP) estimates of the conductivities and dipole moment. The accuracy of our estimates is evaluated by comparing their variances with the corresponding Cramer-Rao bound (CRB). We show that our method provides estimates with variances close to the CRB for sufficiently large data. The results are illustrated by means of numerical examples using different finite approximations in the calculation of the surface potentials, and different SNR values. We also present sensitivity analysis to wrong specification of the source position and to variations in the skull's thickness.

In [32] we present a new formulation for the Magnetoencephalography (MEG) forward problem with a layered head model. The effect of the volumetric currents is expressed in terms of an equivalent surface current density. This current density is the difference between the

volume currents at both sides of the interface between the layers of different conductivity. Thus, it is a 3D vector field with only two significant components since the normal one cancels out. We use the boundary elements method to compute the equivalent current density on the interfaces for a realistic head geometry and obtain the magnetic field with it through an expression not involving conductivities. The matrix associated with the linear system to be solved for the equivalent current density is not singular. This is unlike the traditional formulation, where the electric potential on the interfaces is calculated by means of a singular linear system, causing some numerical difficulties. The current density is a vector constrained to a surface then, for a given number of nodes the associated linear system is twice the size of the electric potentials one. The equivalent surface current density has a higher spatial frequency than the potentials due to its relationship with the gradient of the electric potential. Thus, for the same surface discretization the solution for surface potentials is more accurately represented than that for the current density. The present approach is useful as a redundancy checking, as an aid to (i) the solution of the MEG/EEG inverse problem or (ii) the estimation of the conductivity of the layers.

We present in [33] a method for estimating mechanical properties, active stress and passive elasticity modulus, of the *in vivo* heart using 2D magnetic resonance imaging (MRI) tissue-tagging and intra-ventricular pressure measurements. It has been shown that alterations in these properties may pre-date the onset of certain cardiac dysfunctions. We assume that the myocardium's stiffness tensor is non-homogeneous and propose to model this non-homogeneity using a set of *a priori* known basis functions and the corresponding unknown coefficients. We combine this globally defined physical model with a finite-element formulation and dynamic analysis, and apply non-linear least squares to obtain the unknown parameters (basis functions coefficients.) We evaluate the performance of the proposed estimator by computing the confidence region for the estimated parameters. Numerical examples demonstrate the applicability of our results.

The inverse problem of electrocardiography can be defined as the determination of the information about the electrical activity of the heart from measurements of the body-surface electromagnetic field. The solution to this inverse problem may ultimately improve the abil-

ity to detect and treat cardiac diseases early. In [34], we present an algorithm for estimating the current density of the heart using electrocardiography (ECG) and magnetocardiography (MCG) sensor arrays. We model the electrical activity of the heart using current density represented by a set of spatio-temporal basis functions. In order to solve the corresponding Fredholm equation we apply the element-free Galerkin method and compute the measurements as a function of the torso geometry and cardiac source. Then, we maximize the likelihood function to estimate the unknown parameters assuming a presence of spatially correlated Gaussian noise with unknown covariance matrix.

PhD Graduates:

We have graduated Malcolm Hawkes whose work on acoustic-vector sensor processing is summarized in his PhD thesis [35]. We have also graduated Aleksandar Dogandžić whose work on sensor array processing in correlated noise (for radar and communications) is summarized in his PhD thesis [36]. He has assumed an Assistant Professor position at Iowa State University. Aleksandar received a number of awards, in particular the Outstanding Thesis Award, UIC Division of Engineering, Mathematics and Physical Sciences, 2001.

Transitions:

Our analytical results on performance for radar sensor arrays in [9], [10], are applied to the TechSat21 system. TechSat21, in general, is a radar system using an array of microsatellites. The purpose is to estimate direction, range, and velocity of a ground moving target. Our results are used to predict the performance of this system (e.g. accuracy of estimating the above target parameters in terms of Cramer-Rao bounds and ambiguity functions) and optimally design its configuration. We are also exploring the use of our ideas of vector sensors, which should give a great benefit of removing ambiguities (grating lobes) in direction finding. This work is done in collaboration with Dr. John Garnham [Phillips Laboratory, VTRA, telephone: (505) 846-7224], who provides us with the numerical data for this system.

Researchers from SAIC are currently developing an array of EM vector sensors, following our introduction of this idea several years ago. Contact information: Mr. Ed Gjermundsen,

Senior Staff Member, SAIC. Email: gjermundsene@saic.com. Phone: (703) 861-8711.

Motorola researchers are investigating the use of our OFDM channel estimation algorithms. Contact information: Dr. Timothy Thomas, who collaborated with us. Phone: (847) 538-2586. Email: T.Thomas@motorola.com

Our methods using acoustic vector sensors is continued to be pursued by researchers at NUWC in Newport and resulted in a new transition. These researchers have applied our algorithm in [?] to locate real wideband sources. We are collaborating with them on the analysis and simulation of specific scenarios, and provided them with coded algorithms for the processing of their raw measurements and integration into the experimental hardware and act as consultants. The third stage of this 6.3 project was successfully concluded with demonstrations of our techniques in Lake Seneca in May 2001. Specifically, the algorithm we developed in [?] was applied to locate real sources at depth of 300 ft, distance of 80 ft, with 2 vector sensors at a distance of 12 ft, and the results were very good. NUWC has recently moved to the next stage of 6.4 involving our methods using vector sensors mounted on a submarine. The NUWC project is headed by Dr. Ben Cray [NUWC, Newport, telephone 401-832-8454].

The proposed scheme in [25], [26] of adaptive null-forming scheme for noise cancellation with two nearby microphones, has been included in current hearing-aid products of GN ReSound Corp. These products are available in the world wide market. More details can be obtained from the web site fttp://www.gnresound.com.

Researchers from PTB, Germany, are building an array of EM SQUID vector-magentometers for MEG, following our introduction of the subject to this area. Contact information: Dr. Martin Burghoff. Phone: (030) 3481-238. Email: Martin.Burghoff@ptb.de

References

[1] M. Hawkes, A. Nehorai, and P. Stoica, "Performance breakdown of subspace-based methods: prediction and cure," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp.

4005-4008, Salt Lake City, UT, May 2001.

[2] A. Dogandzic and A. Nehorai, "GMANOVA - A uinified framework for signal processing in correlated noise," submitted.

[3] Y. Huang, G. Friedman, and A. Nehorai, "Balancing magnetic and electric responses of vector-sensing antenna," *IEEE Antennas and Propagation Soc. Int. Symp. and USNC/URSI National Radio Science Meeting,* Vol. IV, pp. 212-215, Boston, MA, July 2001.

[4] Y. Huang, A. Nehorai, and G. Friedman, "Mutual coupling of two collocated orthogonal loops," *IEEE Antennas and Propagation Soc. Int. Symp. and USNC/URSI National Radio Science Meeting,* Vol. 2, pp. 834-837, San Antonio, TX, July 2002.

[5] Y. Huang, A. Nehorai, and G. Friedman, "Mutual coupling of two collocated orthogonally oriented circular thin-wire loops," to appear in *IEEE Trans. Antennas Propagat.*, Vol. AP-51, Apr. 2003.

[6] A. Nehorai, K.-C. Ho and B. T. G. Tan, "Electromagnetic Vector Sensors with Beamforming Applications," in *Handbook on Antennas in Wireless Communications,* L. Godara, ed., pp. 17.1-17.20, CRC Press, 2001.

[7] J. Zhang, C-C. Ko, and A. Nehorai "Source separation and tracking using an electromagnetic vector sensor," *Proc. 34th Asilomar Conf. Signals, Syst. Comput.,* pp. 980-984, Pacific Grove, CA, Oct. 2000. (Invited.)

[8] C-C. Ko, J. Zhang, and A. Nehorai "Separation and tracking of multiple broadband sources with one electromagnetic vector sensor," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 38, pp. 1109-1116, July 2002.

[9] A. Dogandžić and A. Nehorai, "Cramér-Rao bounds for estimating range, velocity, and direction with a sensor array," *Proc. 1st IEEE Sensor Array and Multichannel Signal Processing Workshop,* pp. 370-374, Cambridge, MA, March 2000.

[10] A. Dogandžić and A. Nehorai, "Cramér-Rao bounds for estimating range, velocity, and direction with an active sensor array," *IEEE Trans. on Signal Processing*, Vol. SP-49, pp. 1122-1137, June 2001.

[11] J. Francos and A. Nehorai, "Interference mitigation in STAP using the two-dimensional Wold decomposition model," to appear in *IEEE Trans. Signal Processing*, 2003.

[12] I. S. Yetik and A. Nehorai, "Beamforming using the Fractional Fourier Transform," to appear in *IEEE Trans. Signal Processing*, Vol. SP-51, June 2003.

[13] K. Z. Mao and A. Nehorai, "Feature extraction and classification of hyperspectral data based on geometric shape of reflectance curve," submitted to *IEEE Transactions on Systems, Man and Cybernetics.*

[14] A. Dogandžić and A. Nehorai, "Space-time fading channel estimation and symbol detection in unknown spatially correlated noise," *IEEE Trans. on Signal Processing*, Vol. SP-50, pp. 457-474, Mar. 2002.

[15] A. Dogandžić and A. Nehorai, "Finite-length MIMO adaptive equalization using canonical correlations," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 2149-2152, Salt Lake City, UT, May 2001.

[16] A. Dogandžić and A. Nehorai, "Finite-length MIMO equalization using canonical correlation analysis," *IEEE Trans. Signal Processing*, Vol. SP-50, pp. 984-989, Apr. 2002.

[17] J. Tabrikian and A. Nehorai "Channel equalization in the presence of strong interference sources," *Proc. 2nd IEEE Sensor Array and Multichannel Signal Processing Workshop,* pp. 308-312, Arlington, VA, Aug. 2002.

[18] A. Jeremic, T. Thomas, and A. Nehorai, "OFDM channel estimation in the presence of interference," *Proc. 2nd IEEE Sensor Array and Multichannel Signal Processing Workshop,* pp. 154-158, Arlington, VA, Aug. 2002.

[19] A. Jeremic, T. Thomas, and A. Nehorai, "OFDM channel estimation in the presence of asynchronous interference," to appear in *IEEE Int. Conf. Acoust., Speech, Signal Processing,* Hong Kong, April 2003.

[20] J. Zhu, W. Ser, and A. Nehorai "Channel equalization for DMT with insufficient cyclic prefix," *Proc. 34th Asilomar Conf. Signals, Syst. Comput.*, pp. 951-955, Pacific Grove, CA, Oct. 2000. (Invited.)

[21] M. Hawkes and A. Nehorai, "Acoustic vector-sensor processing in the presence of a reflecting boundary," *IEEE Trans. on Signal Processing*, Vol. SP-48, pp. 2981-2993, Nov. 2000.

[22] M. Hawkes and A. Nehorai, "Acoustic vector-sensor correlations in ambient noise," *IEEE J. Oceanic. Eng.*, Vol. 26, pp. 337-347, July 2001.

[23] M. Hawkes and A. Nehorai, "Distributed processing for 3-D localization using acoustic vector sensors on the seabed or battlefield," *Proc. 8th Workshop on Adapt. Sensor Array Process.*, pp. 91-96, Lincoln Laboratory, MIT, Boston, MA, March 2000. (Invited.)

[24] M. Hawkes and A. Nehorai "Wideband source localization using a distributed acoustic vector-sensor array," to appear in *IEEE Trans. Signal Processing*, Vol. SP-51, June 2003.

[25] F-L. Luo, J. Yang, C. Pavlovic, and A. Nehorai, "A noise-reduction algorithm for dual microphone systems," *IASTED Int. Conf. Signal and Image Processing*, pp. 199-202, Honolulu, Hawaii, Aug. 2001

[26] F-L. Luo, J. Yang, C. Pavlovic and A. Nehorai, "Adaptive null-forming scheme in digital hearing aids," *IEEE Trans. on Signal Processing*, Vol. SP-50, pp. 1583-1590, July 2002.

[27] F-L. Luo, J. Yang, and A. Nehorai, "Spectral contrast enhancement: algorithms and comparisons," Special Issue on Speech Processing for Hearing Aids, *Speech Communication*, Vol. 39, No. 1-2, pp. 33-46, Jan. 2003.

[28] A. Dogandžić and A. Nehorai, "EEG/MEG Spatio-temporal Dipole Source Estimation and Array Design," to appear in *High-resolution and Robust Signal Processing*, A. Gershman, Y. Hua, and Q. Cheng, eds., Marcel Dekker, 2003.

[29] C. Muravchik and A. Nehorai, "Error bounds of EEG/MEG for a stationary dipole source with a realistic head model," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 3763-3766, Istanbul, Turkey, June 2000. (Invited.)

[30] C. Muravchik and A. Nehorai, "EEG/MEG error bounds for a static dipole source with a realistic head model," *IEEE Trans. on Signal Processing*, Vol. SP-49, pp. 470-484, Mar. 2001.

[31] D. Gutierrez, A. Nehorai, C. Muravchik, and J. Lewine, "Estimating Conductivities and Dipole Source Parameters with EEG Arrays, *Proc. 13th Int. Conf. on Biomagnetism, Biomag 2002*, pp. 700-702, Jena, Germany, Aug. 2002.

[32] N. von Ellenrieder, C. Muravchik, and A. Nehorai, "MEG forward problem formulation avoiding the electric potential," *Proc. 13th Int. Conf. on Biomagnetism, Biomag 2002*, pp. 767-678, Jena, Germany, Aug. 2002.

[33] A. Jeremić and A. Nehorai, "Estimating mechanical properties of the heart using dynamic modeling and magnetic resonance imaging," in revision for *Physics in Medicine and Biology.*

[34] A. Jeremić and A. Nehorai, "Estimating current density in the heart using spatio-temporal analysis with ECG/MCG sensor arrays," *Proc. 34th Asilomar Conf. Signals, Syst. Comput.,* pp. 323-327, Pacific Grove, CA, Oct. 2000. (Invited.)

[35] M. Hawkes, "Issues in Acoustic Vector-Sensor Processing," Ph.D. Thesis, Department of Electrical Engineering, Yale University, CT, September 2000.

[36] A. Dogandžić, "Sensor Array Processing in Correlated Noise: Algorithms and Performance Measures," Ph.D. Thesis, The University of Illinois at Chicago, June 2001.